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(NASA Contract No. NASw - 702)

SECOND QUARTERLY STATUS REPORT,
July 15 - October 15, 1963

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON 25, D.C.

R. S. Lowder et al. October 15, 1963 0 refs

A D V A N C E D   K I N E T I C S ,   I N C .

SECOND QUARTERLY REPORT

I) RESEARCH ACTIVITY

During this second quarter of contractual operation, the major emphasis was placed on the development of Langmuir probe diagnostics for the study of a high speed plasma impinging upon a three-dimensional magnetic dipole. A system of ten single Langmuir probes has been constructed and placed in the region of the plasma-field interaction. These probes have made possible simultaneous observation of the plasma at ten different positions with no observable "cross-talk" between the probe signals.

A single probe has also been placed at various points along the dipole-plasma gun line. This probe, lying in the equatorial plane of the dipole, has been used to measure the density of the plasma, the plasma potential and the temperature. It has also been used to determine the position of the boundary of the cavity formed when the plasma impinges upon the magnetic dipole.

Further image converter photographs have been taken simultaneously with the probe observations. Photographs looking perpendicularly to the dipole axis, as opposed to the previous view into the equatorial plane, were also taken.

Finally, further magnetic probe measurements of the increase in magnetic field due to the surface currents in the field-plasma boundary have been made

The months of trouble-free use of the unique vacuum feedthrough used to energize the dipole plus its high current capabilities, low resistance, and low inductance seem to warrant a note soon to be submitted to the Review of Scientific Instruments.

The error noted in the attached report regarding the expression for the current density of the solar wind interface has invalidated the results of several published articles. Therefore, the error will be reported along with a mention of the effects of charge separation at the interface current sheet.

A note regarding the mechanism proposed in the attached report for particle injection into the Van Allen belts will be submitted for publication provided more sophisticated calculations give results comparable to those of the approximate calculations.

Finally, sufficient data of theoretical significance seem to have been taken on this experiment to warrant a paper for the Physics of Fluids following a careful repetition of some of the more crucial tests.

IV) PERSONNEL

The following personnel were engaged in work on this contract during this quarter:

R. S. Lowder
S. W. Lee
A. N. Dienes
R. W. Waniek
H. J. Gilsdorf

determination of the geometrical dimensions of the cavities and their variation with field strength.

Theoretical determination of the magnitude of the magnetic field at the cavity boundary have been reported in the literature, but the accuracy away from the earth-sun line is admitted to be unsatisfactory. Therefore, an attempt will be made to refine the magnetic probe measurements extending the probing to points inside the cavity boundary away from the dipole-plasma gun line.

Also under consideration for next quarter's work is a geometrical rearrangement of the dipole used and its supports so that the phenomena can be observed that occur on the "night" side of the dipole. The theoretical work covering this highly temperature dependent region is at present relatively meager.

III) SCIENTIFIC REPORTS AND PUBLICATIONS

The paper entitled "Approximation of an Ideal Dipole with a Solenoid," by Clark Benson, has appeared in the Journal of Applied Physics, Volume 34, Number 10, page 3136, October, 1963.

A paper entitled "Experimental Observations of Plasma Flow Against a Three Dimensional Magnetic Dipole," by R. S. Lowder, S. W. Lee and R. W. Waniek, will be presented at the November 6, 1963 Meeting of the Plasma Physics Division of the American Physical Society.

f) The shock wave that has been proposed to exist just outside the geomagnetic field-solar plasma boundary is not <u>apparent</u> in our probe and photographic observations, but conclusions cannot be drawn.

g) The image converter observations of the polar region indicate a penetration of the theoretical cavity boundary at the "resultant" poles, i.e., the poles are shifted a few degrees toward the "sun-side" of the dipole axis due to the surface currents in the cavity boundary.

h) The small portion of the downstream profile that is presently observed is approximately in keeping with theory.

i) An error is noted that has been made in published theoretical evaluations of the effects on the cavity profile due to currents in the cavity boundary.

j) A plausible theory for particle injection into the Van Allen belts is formulated and presented along with the above results in the attached report.

II) ACTIVITIES PLANNED FOR NEXT QUARTER

The study of the polar region will be continued in an attempt to see if the cavity profile at the poles is of an unstable form and if the instabilities develop. The system of ten probes, that have verified the qualitative image converter observations of the cavity profile, will be used to try to obtain a quantitative in conjunction with the Langmuir probe observations of the boundary location.

In the attached report, the results of these measurements and the implications that can be drawn at present are given. The principal conclusions are presented here.

a) On the dipole-plasma gun line, the magnetic field inside the solar wind-geomagnetic field boundary is approximately twice the value of the dipole's vacuum field at that point. Thus, the debated assumption of approximate field doubling in theoretical determinations of the boundary appears to be reasonable near the earth-sun line.

b) The plasma pressure appears to be due to a magnetic reflection of the incoming particles and is <u>twice</u> as great as it would be were the particles merely stopped. (The use of this doubling factor has also been a source of debate.)

c) The particles appear to contribute to the plasma pressure only during their single reflection at the boundary.

d) The plasma field boundary away from the poles appears to be stable both during and after initial formation. (Two arguments, apparently missing from the literature, as to why it should be stable are presented.)

e) There does not appear to be any injection mechanism associated with Van Allen belt formation away from the poles.

SCIENTIFIC REPORT

A. INTRODUCTION

In this second quarterly report we present a brief review of the experimental apparatus, a description of the probe arrangements, and then examine some of the questions and problems concerning the solar wind impingement and the Van Allen injection problem to which this data can provide a partial answer.

B. APPARATUS, PROCEDURE AND RESULTS

The general experimental apparatus is shown in Fig. 1. At one end of a glass vacuum chamber, 20 cm in diameter and 60 cm long, is located a conical plasma gun. After evacuation to 10^{-5} Torr, a fast acting gas valve is used to introduce a small amount of neutral hydrogen into the gun where it is ionized and accelerated. The gun fires this plasma whose front is quite planar, and which has a velocity and density, depending on gun operating conditions, of 10^{6} to 5×10^{7} cm/sec and 3×10^{13} to 10^{15} particles/cm^{3}, respectively. Fifty-four cm downstreams from the gun is a one-turn massive coil with a length of 2.54 cm and an i.d. of 2.93 cm that is dimensioned to give a close approximation to a dipole field. The dipole field has been accurately mapped with magnetic probes. With the maximum available excitation current (400,000 A), a field of 300 gauss is produced at 10 cm from the coil axis.

Upon arrival of plasma at the dipole, a cavity is formed that is roughly shaped like a hemisphere centered at the dipole. The dimensions of the cavity are observed to shrink as the current in the dipole coil decreases. There are no betatron effects due to the changing current since all field lines are closed and contained within the cavity, making (d/dt) $\overline{ds} \cdot \overline{B}$ = (d/dt) (0) = 0.

By placing a Langmuir probe at some point along the gun-dipole line (the axis of the vacuum chamber), the probe is found to give no signal while inside the cavity. When the dipole current decreases, the plasma "interface" (the surface of particle reflection) moves inward toward the dipole axis and eventually reaches the probe, the probe then giving a very large positive signal.

If the boundary location were determined solely by equating the field pressure to the plasma pressure, the boundary would move inward with decreasing dipole current, provided the plasma pressure is constant. This is observed to be the case. That is, the plasma pressure during the experimental observation interval is constant within 15% and the field value at the boundary is found to be the same for all dipole currents, only the location of the boundary changes with current.

In Fig. 1A, we show a sample of probe signals for several probe distances from the dipole axis. Fig. 1A (a) is the plasma as seen by a probe 5.6 cm from the dipole axis. The measured density is 8×10^{13} cm^{-3}, and the velocity is 4.5×10^{6} cm/sec. In (c) the probe is 8.13 cm from the dipole axis and the dipole's field at 8.13 cm is 220 gauss when the probe detects the arrival of the interface. In (d) the probe is at 9.4 cm and the field is 200 gauss. In (e) the probe is 10.7 cm from the axis, and the plasma was not completely stopped since here the field was only 130 gauss. For (f) the maximum dipole current was reduced, making the maximum field at the 10.7 cm probe position only 90 gauss, and the plasma was not stopped at all. In (b), however, the probe is only 5.5 cm from the axis. Here, the field is higher than 200 gauss through most of the dipole current half period, and no plasma was observed until the end of the half cycle.

The rate of slow advance of the plasma interface can be computed in the following manner. Let B_f be the field value at the interface, and let r_o be the stopping distance when the dipole's sinusoidal current is a maximum. The distance at which $B = B_f$ is given by

$$B_f\,(r,\,t) = B\,(r = r_o\,,\,t = 2\pi/\omega)\,r_o^3 \sin \omega t/r^3 = B_f\,r_o^3\,\sin \omega t/r^3 \qquad (1)$$

or

$$dr/dt = \omega r_o^3 \cos \omega t/3r^2 \qquad (2)$$

Taking $r_o = 8$ cm and $\cos \omega t \approx -0.7$ then at $r \approx 7$ cm we obtain $dr/dt =$ -6×10^5 cm/sec which compares well with the velocity of the interface advance observed by sequential image converter pictures.

Two magnetic probes were placed along the dipole-gun line to look for a field increase due to particle impingement. These two traces are shown in Fig. 2. The field shown on the lower beam is seen to approximately double with the arrival of plasma. The signal on the "downstream" probe is seen to increase by a similar amount, due to the surface currents in the plasma interface. The drop in signal corresponds to the arrival of plasma.

In Fig. 3, several image converter pictures are shown of the plasma as viewed from above the south pole. Several photographs taken perpendicularly to the dipole axis are shown in Fig. 4. The cavity shape is seen to deviate from a hemisphere in the equatorial plane and to a lesser extent in the meridional plane. The precise shape of this cavity is affected by the presence of a small radial density gradient in the flow (wall effect). This gradient has been measured and will be used to correct the observed shape for precise comparison with theoretically predicted profiles. Even without such corrections, the presently obtained contour agrees reasonably well with computed boundaries (e.g. Spreiter and Briggs), exception made for the polar region.

At the poles, two unexpected phenomena are observed: marked plasma penetration occurs, and the flow past the poles is inhibited. No reasonably well founded arguments can be put forward explaining the polar injection at this time. The lack of flow past the poles may be related to this polar injection. Because the injected plasma is diamagnetic, it will look like a conical current sheet that cancels the field inside it. But it also increases the field outside the cone, causing a larger increase in the magnitude of the dipole field strength on the other side of the poles. Thus the reflection surface is increased to a size too large for our present vacuum chamber.

These two phenomena have been studied recently as a function of inclination of the dipole axis to the flow vector. For this purpose, the dipole is rotated in the vacuum. For an angle as small as 5°, the polar feed actually stops for the pole that is inclined into the plasma flow and is enhanced at the other pole. The "windward" pole, that should be unstable according to theory, appears to be stable to plasma penetration throughout the time of observation, possibly due to strong finite Larmor radius stabilizing effects.

C. INTERPRETATION OF RESULTS

1) ON THE PRESSURE-BALANCE EQUATION

The first problem that we consider is the location of the solar plasma-geomagnetic field boundary on the earth-sun line in the equatorial plane. It is generally agreed that the boundary will be located at the point where the magnetic pressure equals the plasma pressure. This can be expressed, in c.g.s. units as

$$(KB)^2/8\pi = Cnmv^2 \qquad (3)$$

where B is that portion of the field at the boundary due to the geomagnetic field (the total field, KB, being the sum of B and the field due to surface currents at the plasma interface), K and C are constants, n is the plasma density, m is the mass of proton, and v is the component of the ion velocity perpendicular to the interface.

The problem is in choosing the proper values of the constants K and C. For C, several authors have used C = 1 in trying to derive the shape of the cavity. Several other authors have used C = 2 which implies a reflection of each ion off the magnetic cavity, resulting in a momentum change of 2 mv. For K, values between 1, 2 and 3 have been suggested and used. Beard has tried, recognizing that $KB_d - B_d$ is due to all currents in the curved interface, to determine the right value for K. He concludes that 2 would be close to the appropriate values near the earth-sun line. However, Midgely and Davis indicate, as a conclusion from other assumptions, that perhaps K should be about three. We now examine our data.

In Fig. 6 the upper beam shows the Langmuir probe signal, with magnetic field, (a), and without magnetic field, (b). The lower beam is the dipole current or the magnetic field. The probe bias voltage is 20 volts. Without field, the 7.5 volts probe signal is drawn through 52 ohms. Although the use of 52 ohms does decrease the applied voltage appreciably, such value is used to eliminate signal reflections. Smaller terminating resistors do not decrease the current drawn because the probe still carries maximum ion current at 12.5 volts. The total area of the cylindrical probe is 0.007 cm^2, or its effective area, A, is $0.007/\pi = 0.0022$ cm^2. Equating the current to nevA, with v, the velocity, being 5×10^6 cm/sec, we obtain a density of 8×10^{13} cm^{-3}. Then we compute the values of B_d, the vacuum dipole field, that should stop this plasma. Equating magnetic pressure to field pressure, we let $(KB_d)^2/8\pi = Cnmv^2$. Thus the predicted B_d for stopping is $(C/K^2)^{1/2}\,(8\pi nmv^2)^{1/2} = (C/K^2)^{1/2}$ 284 gauss. The value of B_d as measured by the lower trace of Fig. 6 amounts to 220 gauss at the probe location of 8.1 cm. Equating the predicted B_d to this measured value and solving for C/K^2, we obtain $C/K^2 = 0.6$. This value is typical; values obtained from such calculations ranging between 0.5 and 0.7.

As stated above, values of $K = 1$, 2, or 3 and values of $C = 1$ or 2 have been suggested. Combinations of these values yield $C/K^2 = 1/9$, $2/9$, $1/4$, $1/2$, 1, or 2. Only $C/K^2 = 1/2$ is close to the measured value. This implies $C = 2$ and $K = 2$.

There are a few possible errors in this measurement of C/K^2. The first error is a 10% error in measuring the value of the total cross sectional area of the probe. In addition, an uncertainty is introduced in the effective area of the cylindrical probe since this parameter is a function of the plasma temperature. Only for a zero temperature streaming plasma can the effective area be equated to length times diameter. While a small random velocity superimposed on the streaming velocity should not significantly alter the interaction, it would increase the effective area of the probe. Correcting for this would yield a lower density, a lower predicted B, and a higher value of C/K^2. Also, the establishment of a sheath on the probe would increase the effective area.

Another possible error is in interpreting the measured reflecting field to be the field at the probe position at the time of probe detection of the deflecting ions. If the interface is located at r, then the protons are reflected by entering the cavity and making a 180° turn. In doing so they penetrate to the point $r - \Delta r$, where Δr is a function of the proton Larmor radius and the electric field due to the steady state proton density concentrated near $r - \Delta r$. Thus, the probe measures $r - \Delta r$ rather than r. The appropriate magnetic field value would be approximately the value at $r - 1/2\ \Delta r$. Taking Δr to be about one centimeter, one obtains for the analysis above a C/K^2 value of 0.46 instead of 0.6. It would seem that the error is a non-linear function of r and that possibly a careful examination of the measured value of C/K^2 versus distance from the dipole could reveal the actual value of Δr as a function of r.

The C/K^2 value can be shown to be unaffected by the finite electron temperature. The simplest argument is to say that the electron pressure is due to momentum change at the boundary and the average change per electron is the same as in the zero-temperature case, namely, $2m_e v$, where v is the group velocity. The number of electrons reflected per unit time per unit area remains less than that of the ions by the ratio of their masses, and hence electron pressure is negligible. (A similar result can be obtained by using the alternative boundary condition, $J = B/4\pi$, where J is the interface current density, and by showing J due to electrons to be the same as for zero termperature and negligible compared to the ion contribution.)

Another feature of the interaction whose effect must be determined is that the ion mean free path is, for $n \approx 8 \times 10^{13}$, less than a few centimeters. The effect on the C/K^2 value of two or three collisions between a reflected and an incoming particle is unclear. From the point of view of plasma physics the case of very short mean free path with the resultant slow plasma diffusion across the boundary would be of interest. For this experiment however, long mean free paths are desirable to insure pure reflections at the boundary.

2) ON THE STABILITY OF THE BOUNDARY

Some authors have suggested that the interface may be unstable (Parker). Others have argued that the front may be unstable when there is a sudden increase in plasma density (e.g. at the onset of a magnetic storm; for discussion see Axford). However, the photographs of the plasma show no visible evidence of any instability at the interface either after the interface is formed or during the time of plasma arrival and cavity formation, which simulates the solar flare arrival.

The instabilities proposed would appear in the form of flutes which should be visible in this experiment if the wavelength is greater than a few millimeters. It has been argued (Axford) that the advancing interface is stable, since the center of curvature of the field lines lies in the field. However, a much more rigorous argument can be given for stability if one uses the energy principle developed by Rostoker and further employs the flux tube-plasma tube interchange method.

Furthermore, even if the front were susceptible to flutes, it has been shown that the inequality in ion and electron ExB drift velocities resulting from the ions finite and larger Larmor radius tends to stabilize a "fluted" plasma boundary by greatly reducing the flute growth rate (Rosenbluth, Hoh). In both our laboratory plasma and in the solar plasma, the ion Larmor radius is finite and larger than the electron Larmor radius. Thus the stabilizing effect applies also to this experiment.

3) ON THE PROBLEM OF SPECULAR REFLECTION

In theories aimed at determining the cavity boundary, the assumption has been made that the particles are reflected once and only once by the magnetic field and that as they travel away from the magnetic field, they do not change the characteristics of the incoming plasma. The best experimental evidence we have for this assumption is the observation that the plasma boundary advanced only as fast as the point of constant $B^2/8\pi$ moved inward due to the decay of the dipole current. That is, if the particles would build up at the boundary, the total pressure should increase with time as flow continues, therefore, the balancing field at the boundary should also increase with time.

We infer no such increase in total plasma pressure from the consistency in the measurements of the balancing field pressure at boundary location.

D. CONSIDERATIONS REGARDING THE VAN ALLEN BELT

1) PROBLEMS REGARDING NON-POLAR INJECTION MECHANISMS

It has been suggested that through some instability mechanism such as fluting, turbulence or oscillations, the interface may become distorted and a small volume of plasma may break away into the field. Such a plasmoid would not be stopped by any magnetic field, since the plasmoid's initial motion through the field causes it to become polarized, the dynamics being the motion of an electric dipole moving perpendicularly to a magnetic field. In the space situation, the plasmoid would move toward the earth until it reached the point where the magnetic field lines pass through the conducting exosphere. The polarization is shorted out, and the magnetic field then stops and traps the plasmoid at the Van Allen belt.

The mechanism is quite reasonable were there any indication that such plasmoids could be formed out of the plasma interface during magnetic storms. However, in this experiment we see <u>no</u> indication of such plasmoid generation even during the initial formation of the cavity when the plasma pressure is very rapidly increasing.

Thus, we must look for another injection mechanism. From a study of our data, there seems to be no indication at this time of injection in the region near the equatorial plane. Hence, we examine the polar region for a possible injection mechanism.

2) POLAR INJECTION

C. C. Chang has given reasons to suspect a polar injection mechanism. He points out that the plasma cavity surface is unstable at the poles (as concluded by most authors in deriving the shape of the cavity) and thus particles can penetrate the cavity. They travel down the field lines until they reach their "mirror point" (determined by their velocity perpendicular to the magnetic field line) where they are reflected out of the cavity. Chang speculates that if there should be a mechanism such as collisions or other short time disturbances that could cause a diffusion or other displacement of a particle off its guiding field line, the particle would then travel out along this new field line, which may lie in the apex of the Van Allen belt. Such a mechanism for displacement into the Van Allen belt is proposed in this quarterly report.

3) A PROPOSAL FOR A NEW MECHANISM OF VAN ALLEN BELT INJECTION

As pointed out above, a mechanism has to be found which causes plasma particles near the poles to move into the Van Allen belt. Such a mechanism would be brought about by having an electric field everywhere perpendicular to the magnetic field lines (i.e., a circular electric field about the polar axis) such that all the particles would have a drift velocity of $\bar{E}x\bar{B}/B^2$ perpendicular to the field lines and in the direction of the Van Allen lines. Thus the particles would drift to the Van Allen lines and be trapped within the belt.

A negative $d\Phi/dt$ at the poles, where Φ is the flux through the surface enclosed by a circular electric field line, would produce such an electric field. But just such a reduction in Φ would take place if there were either an increase in the surface current or an inward advancement of this surface current boundary.

And finally, we note that both an increase by several orders of magnitude in this surface current and a rapid inward advancement of this current sheet take place when the "quiet" solar wind is interrupted by the arrival of the high speed, high density plasma of a solar flare.

Thus upon the arrival of a plasma of high energy density, the resultant decrease in field in the polar region would cause the particles of the quiet wind that are near the poles to drift into the Van Allen belt. Any additional particle entering the polar region while the current sheet is increasing and advancing may also be injected. The initial assumption that the actual quiet plasma-field boundary is roughly cone-shaped at the poles, due to the polar instability of the theoretical profile, is not needed. The lack of instability induced penetration merely increases the drift distance necessary for trapping.

A rough calculation of the net drift illustrates the plausibility of this injection scheme. Consider a solar flare plasma with a density of 10^4 cm^{-3} and a velocity of 10^8 cm/sec. This plasma is stopped where $(2B_d)^2/8\pi = 2nmv^2$ or where $2B_d = 9 \times 10^{-2}$ gauss. The resultant surface current sheet can be approximated by a solenoid 5 to 8 earth radii long with a radius equal to the equatorial plane distance from the earth's axis to the plasma boundary. Actually, only the ratio of the radius to the height of the solenoid is important so that we know the ratio between the solenoid's wall field, $2B_d - B_d$ and its axial field. Take the axial field due to the new plasma surface to be 1/5 the wall field or $1/5 B_d$. Consider some point a distance, r, from the axis. The electric field is $E = (1/2\pi r)(d\Phi/dt)$. Assuming the new axial field due to surface currents to be much larger than that due to the previous quiet wind, the rate of increase of the solenoidal field is approximately constant during the arrival time Δt, and we obtain

$$E = 1/2\pi r\,(\Delta\Phi/\Delta t) \approx 1/2\pi r\,(\pi r^2\ 1/5 B_d/\Delta t) \tag{4}$$

At a point where the field is B, the drift velocity, $\bar{E}\times\bar{B}/B^2$, is

$$v = rB_d/10B\Delta t \tag{5}$$

and the distance the plasma travels is

$$d = v\Delta t = r/10(B_d/B) \text{ meters} \tag{6}$$

Since the plasma boundary is approximately equidistant from the center of the earth

$$B_d/B \approx 1/2 \tag{7}$$

Thus,

$$d \approx r/20 \tag{8}$$

For r = an earth radius, the particles move perpendicularly to the field, a distance of 3×10^5 meters away from the poles and towards the equatorial plane, into the Van Allen belt.

Before any real faith can be placed in the above theory as being an injection mechanism, one must do a more careful analysis to see if the injection distance is sufficiently large. These theoretical predictions should be compared with known solar flare events.

It does appear, however, that drift velocities and drift distances are not negligible during changes in the solar wind pressure and need to be accounted for in predicting the dynamics of solar wind effects.

E) NOTE REGARDING PUBLISHED CALCULATIONS OF THE EFFECT OF INTERFACE SURFACE CURRENTS

In the article, "The Interaction of the Terrestrial Magnetic Field with Solar Corpuscular Radiation, 2. Second Order Approximation," by David B. Beard, Journal of Geophysical Research, 67, 477 - 483, 1962, the basis for the second approximation is a calculation of the magnetic field throughout the cavity resulting from the interface surface current. This surface current is due to the reflection of ions and electrons at the boundary. Letting the surface current density at the earth-sun line be J_o, an initial assumption is made that the surface current density at any point is given by

$$J = J_o \cos\alpha \qquad (9)$$

where α is the angle between the solar wind and the normal to the surface.

The correct expression for the current density at the boundary is

$$J = 2nmv^2 \cos^2 \alpha / B \qquad (10)$$

where B is the magnetic field at the boundary, n is the plasma density, m is the ion mass and v is the ion velocity.

For the <u>actual</u> cavity boundary, $B = B_o \cos \alpha$, and in this special case

$$J = 2nmv^2 \cos \alpha / B_o = J_o \cos \alpha \qquad (11)$$

However, for the above paper's assumed hemispherical surface, B is not equal to $B_o \cos \alpha$. Therefore it should be realized that the use of $J = J_o \cos \alpha$ is also an approximation, but perhaps an appropriate one.

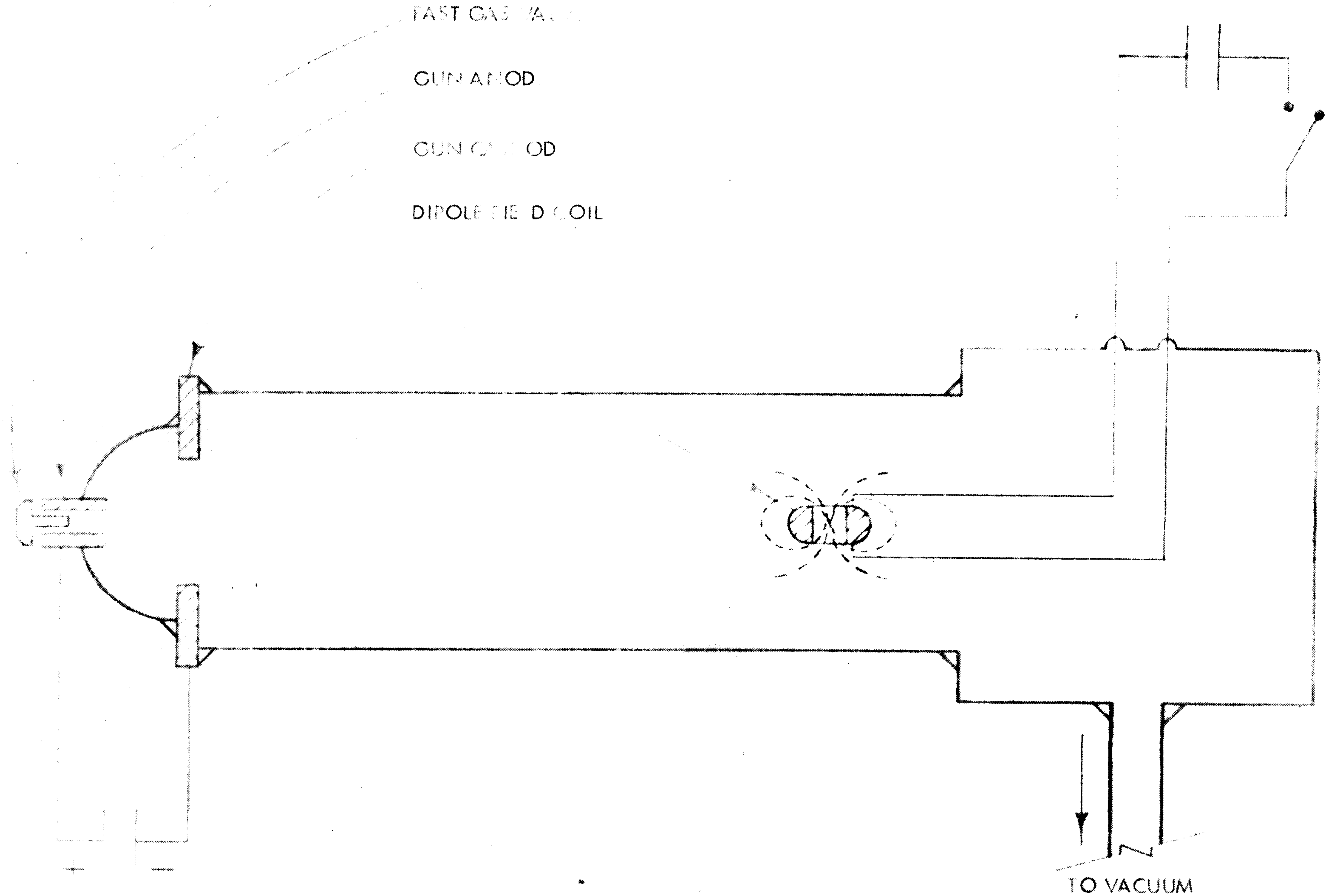


Fig. 1 SCHEMATIC OF APPARATUS

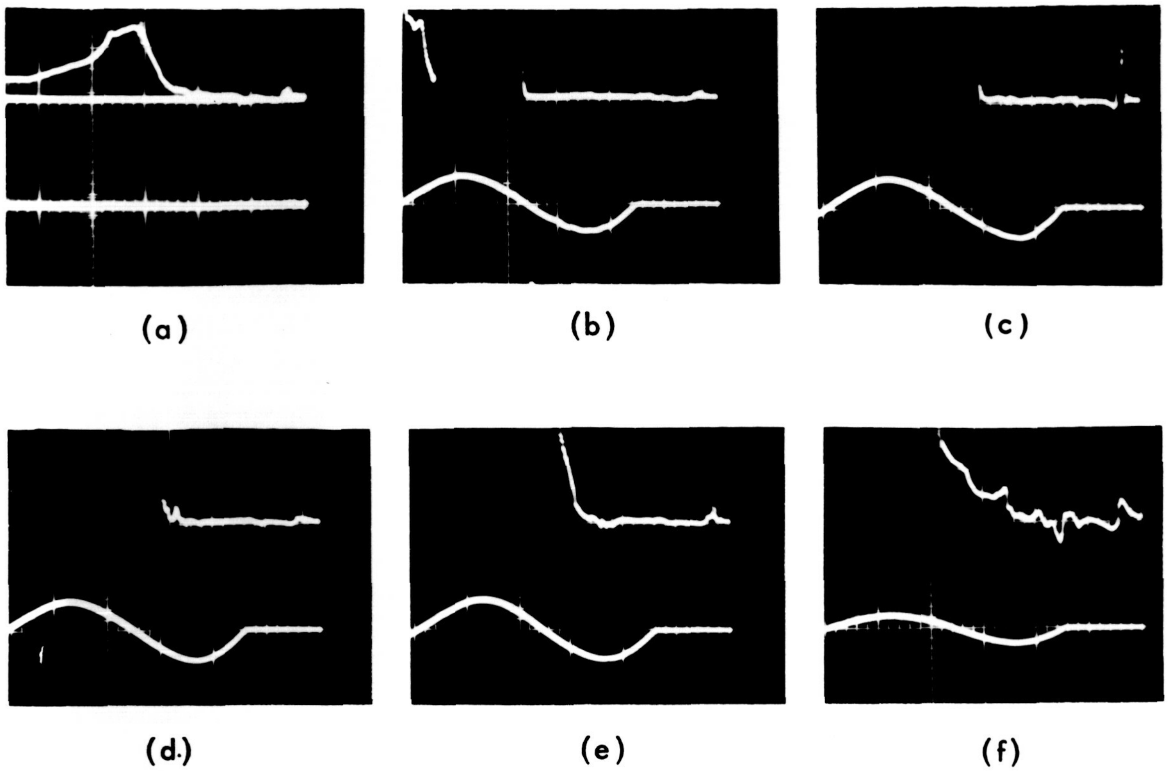


Figure 1A Upper beam: Langmuir probe observations along the dipole-gun line. (Trace sweeps right to left at 5 μsec/cm and 5 volts/cm.) The lower beam is the magnetic field. (0.2 v/cm.) (a) is the probe signal for no magnetic field.

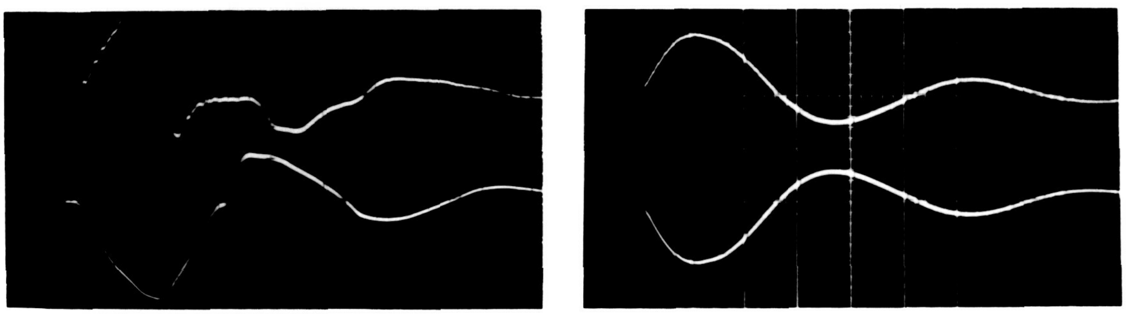
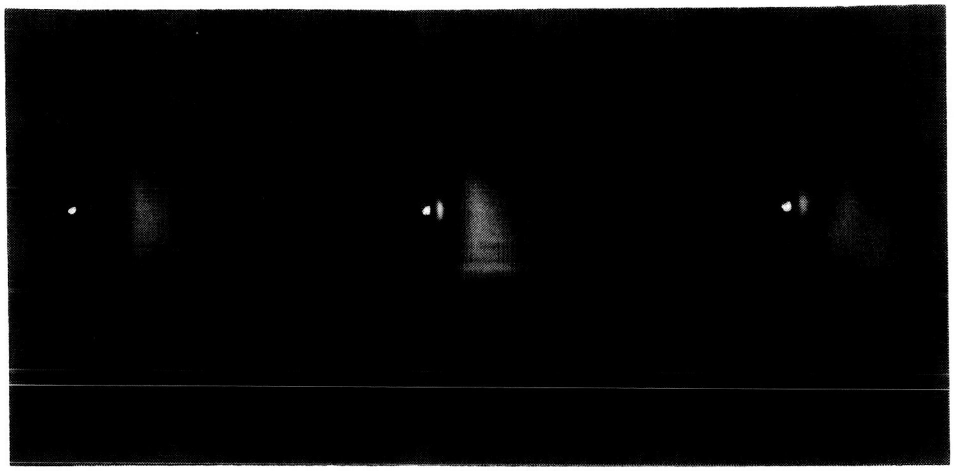
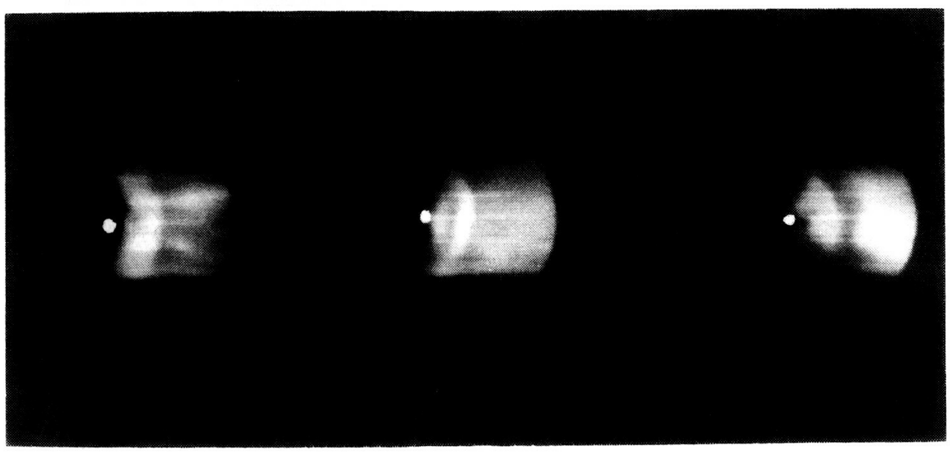


Figure 2. Magnetic field increase. The upper beam is the signal from a magnetic probe located 4.5 cm from the dipole axis. The magnetic probe of the lower beam is located 8.2 cm from the axis. The left picture is the signals without plasma impingement, and the right is with the added field of the surface currents. (Upper beam: 5 μsec/cm, 0.2 v/cm. Lower beam: 0.01 v/cm.)

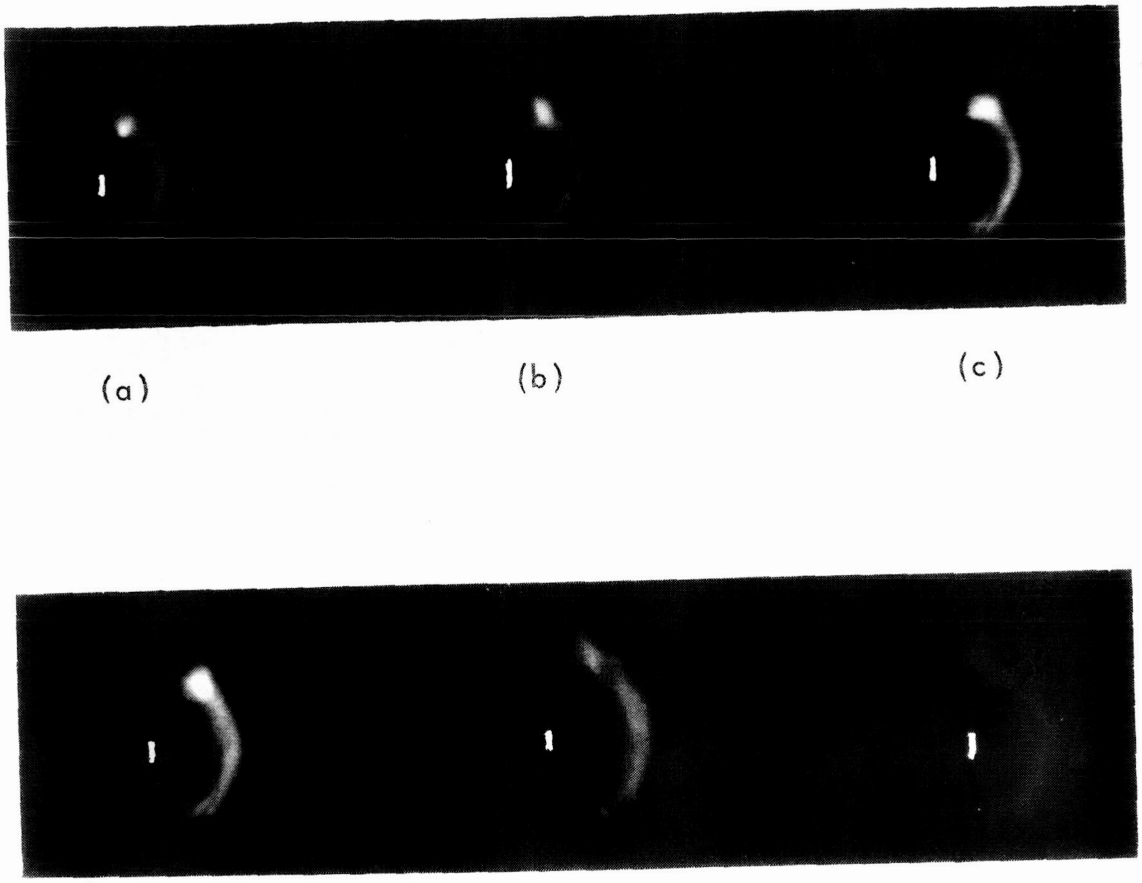


(a) (b) (c)



(d) (e) (f)

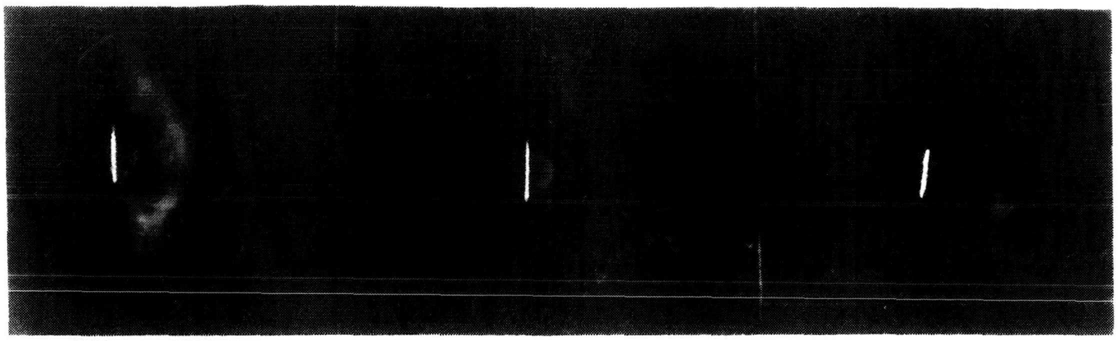
Figure 3. Image converter photographs taken from above the south pole, looking parallel to the axis. (a), (b), and (c) are pictures of initial cavity formation for three different plasma densities and velocities. (d), (e), and (f) show the boundary later in time and close to the dipole due to reduced dipole current. The white dot is the dipole axis location. (f) shows the dark (i. e., less luminous) region between the cavity wall and the incoming plasma. The dark region shown here is three to five times thicker than is usually observed.



(a) (b) (c)

(d) (e) (f)

Figure 4. Image converter photographs taken perpendicular to the dipole axis. (a) and (c) are the same as (b) except that (b) has more observable polar plasma penetration. (d) and (e) are for higher dipole currents, but the same plasma momentum and density. (f) is for a lower plasma current and a lower plasma density



(a) (b) (c)

(d) (e) (f)

Figure 5. Image converter photographs of plasma-field interaction taken perpendicular to the dipole axis. The angles of the "equator" below the "earth-sun line" are: (a) 0°, (b) 2.5°, (c) 4.3°, (d) 8.7°, (e) 25°, and (f) minus 10°. The dipole is necessarily moved somewhat off axis to obtain these angles. The white line is the dipole axis, where the angle has been drawn with respect to the figure page.

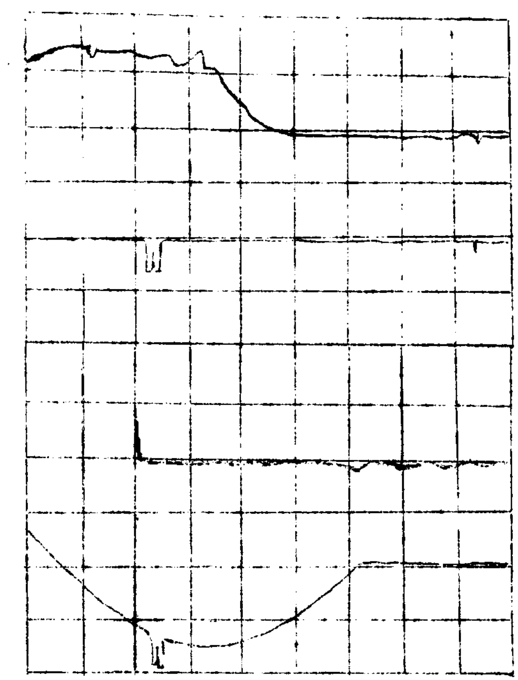


Fig. 6 PROBE MEASUREMENT OF BOUNDARY FIELD AND PLASMA DENSITY

Upper Beam is the Langmuir Probe at 5 volts/cm.

Lower Beam gives the Magnetic Field.

Sweep Speed is 2 μsec/cm. Upper pair is without field; lower pair of traces is with field.